

<b>REPORT DOCUMENTATION PAGE</b>				<i>Form Approved</i> <b>OMB No. 0704-0188</b>		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.						
<b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>						
<b>1. REPORT DATE</b> (27-10-2009)27		<b>2. REPORT TYPE</b> Final Technical Report		<b>3. DATES COVERED</b> (From - To) 01 Feb 2008 - 31 Jul 2009		
<b>4. TITLE AND SUBTITLE</b> Cooperative Autonomous Underwater Vehicles Used to Search Large Ocean Areas for Mines				<b>5a. CONTRACT NUMBER</b>  		
				<b>5b. GRANT NUMBER</b> N0014-08-1-0276		
				<b>5c. PROGRAM ELEMENT NUMBER</b>  		
				<b>5d. PROJECT NUMBER</b>  		
<b>6. AUTHOR(S)</b> Edwards, Dean B.				<b>5e. TASK NUMBER</b>  		
				<b>5f. WORK UNIT NUMBER</b>  		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> University of Idaho, Office of Sponsored Programs Morrill Hall Room 414 PO Box 443020 Moscow, ID 83844-3020				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  		
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research 875 N. Randolph Street Arlington, VA 22203-1995				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR		
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b> PR# 08PR03449-01		
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> Unlimited						
<b>13. SUPPLEMENTARY NOTES</b>  				20091030491		
<b>14. ABSTRACT</b> The overall objective of the research was to develop and apply strategies for autonomous collaboration among UUVs to search for underwater mines. We successfully simulated six behavior modules including Navigation and Formation Control, Vehicle Replacement, Divert to MLO for Inspection, Leader Replacement, Deployment and Recovery, and Multi-Vehicle Sensing. All these modules were implemented and simulated on the MOOS platform except for Multi-Vehicle Sensing. We also defined and developed a mapping strategy for UUVs. The UI strategy creates a multi-layered map of the search space that contains information about fleet UUV positions, area coverage, low-resolution MLO position estimates, dangerous areas, and high-resolution MLO position estimates. We developed a fuzzy logic Supervisor/Planner module that operates in both a centralized and decentralized fashion to satisfy a variety of constraints and optimize time and energy resources for a fleet of UUVs. With these results we have satisfied all the requirements of our Baseline funding. In addition, we modified our communication protocol to a token-passing architecture in order to implement the UC2I reference mission using our modules with the Backseat/Front seat paradigm. We also located and bench tested a small Linux board in order to implement MOOS with a "backseat driver" paradigm on our UUVs.						
<b>15. SUBJECT TERMS</b> Multiple Autonomous Underwater Vehicles, Mine Counter Measures, Collaborative Behaviors, Vehicle Communications						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UU		<b>18. NUMBER OF PAGES</b> 5	
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U	<b>19a. NAME OF RESPONSIBLE PERSON</b> Dean B. Edwards		<b>19b. TELEPHONE NUMBER (Include area code)</b> 208-885-7229	

# **Cooperative Autonomous Underwater Vehicles Used to Search Large Ocean Areas for Mines**

Dean B. Edwards  
Department of Chemical Engineering  
Center for Intelligent Systems Research  
University of Idaho  
Moscow, ID 83844

Phone: (208) 885 7229 fax: (208) 885 6840 email: [dedwards@uidaho.edu](mailto:dedwards@uidaho.edu)

Grant Number: N00014-08-1-0276  
<http://www.mrc.uidaho.edu/cisr/subs/>

## **LONG-TERM GOALS**

The long term goal of this project is to find all mines in a large area of the ocean in an efficient manner. We will pursue a collaborative, adaptive strategy for identifying and assessing mine-like objects (MLOs) that enables unmanned underwater vehicles (UUVs), which we also mean to be autonomous, to share resources in order to reduce search time and more evenly distribute energy consumption. The control and communication algorithms developed in this work will help UUVs to better communicate with each other so they can cooperate and be more efficient at finding mines.

## **OBJECTIVES**

The overall objective of the research is to develop and apply strategies for autonomous collaboration among UUVs to search for underwater mines. Formation-flying and underwater communication among multiple vehicles allow automated deployment, coordinated sensing, diversion of vehicles to obtain high-resolution information, and mapping to optimize return of information given expenditures of time and energy. All behavior and planning modules have been developed under the MOOS API and libraries and adhere to the software architecture specified for the UC2I Program.

## **APPROACH**

Our research enables cooperative activity using a language to motivate and control behaviors in the context of regulated formation-flying. Formation-flying is an underlying behavior governed by a regulation algorithm. The other behaviors, including deployment, vehicle replacement, leader replacement, divert to inspect a MLO, and mapping, are controlled by exchange of underwater messages in a language. These approaches have been simulated and tested to ensure that cooperative capabilities are possible within underwater communication and navigation constraints, and that the software is portable to deployable systems. The formation-flying and basic behavior algorithms have been developed and the software is MOOS compatible. The Autonomy System we have developed comprises six behaviors or modules that provide input to our Supervisory/Planner module. The six behaviors are Navigation and Formation Control, Vehicle Replacement, Divert to MLO for Inspection, Leader Replacement, Deployment and Recovery, and Multi-Vehicle Sensing. The Supervisory/Planner module is able to satisfy a variety of constraints and optimize time and energy resources for a fleet of



UUVs while still providing for proper confidence for MLOs encountered during MCM missions. In addition, the Supervisory/Planner module implements the UI mapping strategy which utilizes low-bandwidth acoustic communication to populate and maintain a distributed representation of the search area among a small fleet of autonomous underwater vehicles.

## WORK COMPLETED

Work was performed on the UI Autonomy System that consists of six behaviors or modules that provide input to our Supervisory/Planner module. The six behaviors are Navigation and Formation Control, Vehicle Replacement, Divert to MLO for Inspection, Leader Replacement, Deployment and Recovery, and Multi-Vehicle Sensing. With the exception of the Multi-Vehicle Sensing module, all the modules have been successfully simulated on the Autonomous Littoral Warfare Systems Evaluator-Monte Carlo (ALWSE-MC), which is a software package developed at Panama City. We have also developed a fuzzy logic Supervisory/Planner module that makes decisions about the need to finish a mission on time while searching an area as thoroughly as possible. A number of these algorithms have also been implemented on the MOOS software platform and run with MOOS simulation software as explained below.

### UI MOOS software modules:

The UI Autonomy System is designed to conform to a “modular behavior-based autonomy” paradigm, where fleet actions can be decomposed into behaviors that will run on any MOOS-compliant system. The actions resolve into four groups, divided into separate tasks in the original proposal. These groups and their associated actions are as follows:

- A. Basic Fleet Behaviors: these include actions required for fleet maintenance, such as navigation and formation control, vehicle replacement, leader replacement, and divert to inspect point of interest. These have been successfully tested in the context of a mine countermeasure (MCM) mission in ALWSE-MC and in MOOS. Results of this work have been reported in Johnson, et al., “Collaborative Mapping with Autonomous Underwater Vehicles in Low-Bandwidth Conditions,” *IEEE-Oceans Bremen*, Bremen, Germany, May 2009, and in Frenzel et al., “A MOOS module for autonomous underwater vehicle fleet control,” in *Proc. Oceans 2009 – MTS/IEEE Biloxi*, Biloxi, Mississippi, October 2009.
- B. Deployment and Recovery: these actions have been designed and simulated in the context of MCM missions using ALWSE-MC and in MOOS.
- C. Supervisor/Planner: a UI fuzzy logic MOOS suite that allocates resources depending on time, Mine-Like-Object density, and remaining energy has been developed and implemented. The supervisory/planner module uses a fuzzy logic control system to vary vehicle and formation base speed to balance energy and time requirements against the need to achieve complete coverage in a MCM mission. This module has been successfully tested in ALWSE-MC. Results of this work have been reported in Hallin, et al., “A Fuzzy Logic Resource Optimizer for a Fleet of Autonomous Vehicles in Low-Bandwidth Conditions,” *IEEE-Oceans Bremen*, Bremen, Germany, May 2009.
- D. Mapping: A layered strategy for real-time map construction across the fleet using acoustic communications has been developed and tested in ALWSE-MC. Results of this

work have been reported in Johnson, et al., "Collaborative Mapping with Autonomous Underwater Vehicles in Low-Bandwidth Conditions," *IEEE-Oceans Bremen*, Bremen, Germany, May 2009.

Acoustic communication involving the AUVish language and the WHOI modem is used to support the information transfer necessary for collaborative action. Through many of the simulations and field tests, AUVish messages have been communicated using a TDMA (time-division, multiple-access) protocol that runs in a 30-second cycle. Recently, we have modified the communication protocol to conform more closely to a token-passing architecture. With this approach, vehicles transmit messages only after receiving a virtual "token" from the previous vehicle in the communication cycle. This modification to the communication cycle (i.e. token-passing) will allow us to implement communication from the backseat where messages are formed to the front seat which controls the WHOI modem. The token-passing protocol allows us to implement the UC2I reference mission, see figure below, without the need for the TDMA protocol.

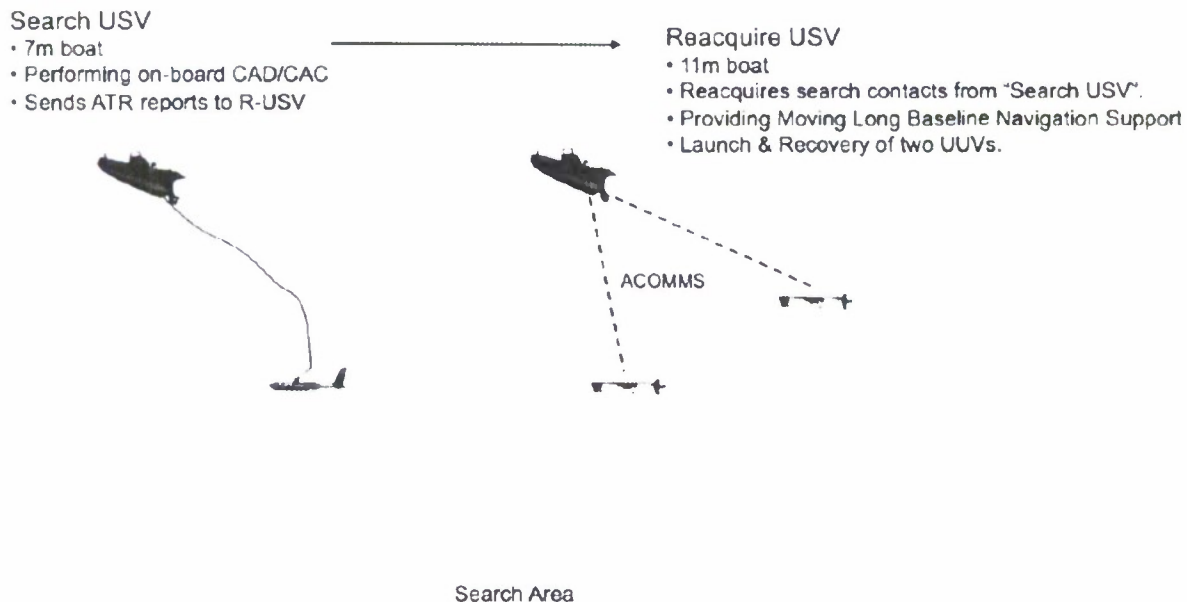


Figure 1. UC2I Reference Mission consisting of one search USV and one reacquire USV working with two UUVs

The MOOS software that we have developed allows a fleet of vehicles to autonomously perform an MCM operation embedding the previously described actions that balances time and energy with coverage. These actions have been verified in MOOS simulations. The University of Idaho's Software Repository presently consists of the following modules:

***pFleetControl*** This MOOS module, working in conjunction with the Waypoint behavior, controls a single vehicle operating as a member of a fleet of up to five vehicles in a leader/follower sweep formation. Individual roles and formation geometries are specified in the mission file. Supports vehicle and leader replacement and divert to inspection. Information is shared across the fleet using UI AUVish messages broadcast on a fixed timing cycle.



**iSerialPort** This MOOS module is used to send and receive UI AUVish messages via a WHOI modem in support of pFleetControl. Supports both 13-bit and 32-Byte messages, as defined in the UI packet specification.

**pEnergyMonitor** This module reads from the mission file a polynomial characterizing the instantaneous power as a function of speed for a specific vehicle. Using this equation and an initial energy capacity, the application tracks energy consumption and posts remaining capacity.

**pFuzzifier** This is the first of three modules in the Fuzzy Logic Suite. Input variables and their associated membership functions are read from the mission file. Based on the specified input variables, the module receives numerical (“crisp”) values from the database and posts “fuzzy” values (i.e., membership sets and percentages).

**pInference** The inference module reads a set of fuzzy logic rules from the mission file and, based upon fuzzy input values received from the MOOSDB, posts fuzzy output variables back to the database. There is one rule for each fuzzy output variable and consists of fuzzy input variables, Boolean operators, and parentheses.

**pCrisper** The final module in the suite reads definitions of output membership sets and associated “singletons” (i.e., “crisp” output values) from the mission file. Using this information and messages posted by pInference, pCrisper posts “crisp” (numerical) values back to the database.

**pConvert** Similar to pEchoVar, but with added capabilities. To facilitate using the Fuzzy Logic Suite to post updates to other modules, this MOOS module will subscribe to input variables and repost them to the database under new names, new formats (double vs. string) and with specified prefixes.

**pMissionTime** In order to balance speed versus time, a module was developed that reads a set of waypoints from the mission file, as well as a time requirement, and then during a mission posts an estimate of how much residual time will be left at completion.

**uFuseGrid** This utility builds upon the work originally done by Andrew Shafer at MIT. It accepts multiple map files produced by pArtifactMapper as input and produces a unified map file, containing information collected across a fleet of vehicles.

**uShowGrid** This utility is for post-mission analysis of an MCM mission. It accepts a map file, corresponding to one or more vehicles (see uFuseGrid) and displays the results graphically. Uses the 2D graphics library, g2. ([g2.sourceforge.net](http://g2.sourceforge.net)).

With these MOOS software modules, we have implemented all of the behaviors we proposed to develop in the Base effort part of this project. We have documented most of these MOOS modules in the University of Idaho’s Software Repository. We also have implemented, in MOOS, the token-passing communication protocol previously discussed. Again, this modification allows us to use the Backseat/Front seat autonomy paradigm with existing MOOS modules and to implement the UC2I reference mission.

We have located a Linux board that can be installed in our UUVs and have successfully compiled the MOOS database on this board. When this board is operational in our UUVs and the token-passing communication protocol is implemented, we will be able to test our autonomy MOOS modules on our

vehicles and run the UC2I reference mission. In addition, our MOOS control and communication protocol would allow for the UUVs to demonstrate autonomy and participate in operations where the USV acts as the fleet leader. This testing would be done at Bayview, Idaho and would be part of the efforts proposed in Option 1 and 2.

#### **Multi-Vehicle Sensing:**

Because the CAD/CAC system is presently being better defined in MOOS, we have not been able to implement this module in MOOS. Most of our work in this area investigated the generic question of distributed detection of a discrete-valued underlying scene from a network of noisy sensor measurements of that scene. In particular, we developed an algorithm where each sensor in the network can compute the most probable underlying scene, given the observations of all the sensors. That is, we showed how the global MAP estimate for the underlying scene can be found in a distributed manner. Our strategy is based on applying a diffusive agreement protocol. An example of the application of agreement and agreement law design for maximum *a posteriori* probability (MAP) detection is discussed in our work, see Sandip, et. Al. "A control-theoretic perspective on the design of distributed agreement protocol," *International Journal of Robust Nonlinear Control*, vol. 17, pp. 1034-1066, 2007.

#### **UI mapping strategy:**

The UI mapping strategy utilizes low-bandwidth acoustic communication to populate and maintain a distributed representation of the search area among a small fleet of autonomous underwater vehicles. The algorithm used for implementing this strategy and the map generated with this algorithm is part of the Supervisory/Planner Module. Using available acoustic communications, the individual vehicles create a multi-level representation of the search area. A low-resolution map contains information about the positions of other vehicles in the fleet (Figure 2), estimated coverage of the search area (Figure 3), low-resolution MLO locations (Figure 4), and potentially dangerous areas for the UUVs.

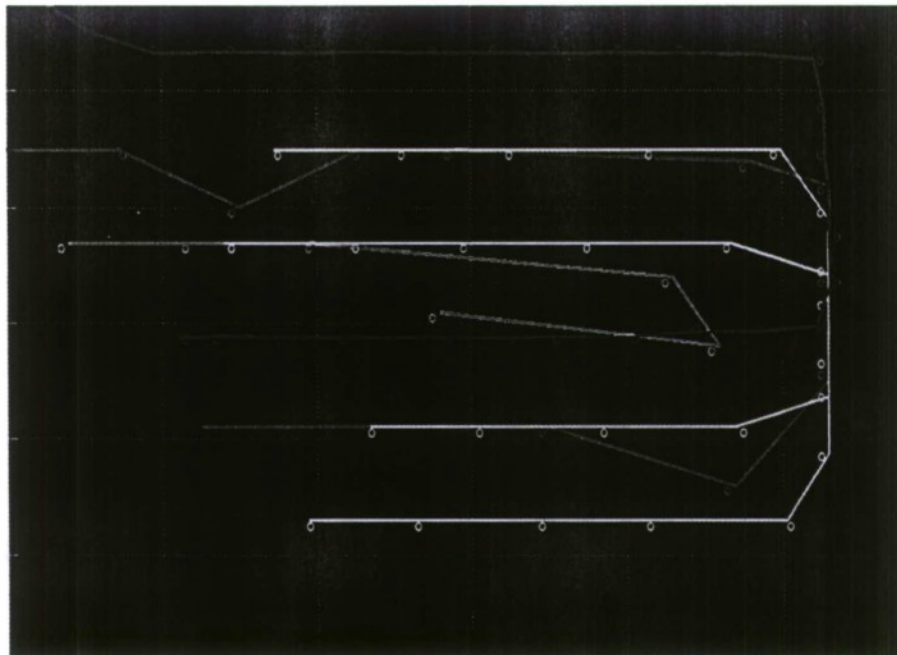


Figure 2. Graphical representation of vehicle position estimates as made by Vehicle 1 (red) for all UUVs in the fleet.